

Continuous-Wave 4.3- μ m Intracavity Difference Frequency Generation in an Optical Parametric Oscillator

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14. ABSTRACT We have achieved 150 mW of cw output at 4.3 μ m, using difference frequency mixing in a singly resonant optical parametric oscillator (OPO). We pumped the OPO cavity, which contains periodically poled LiNbO ₃ (PPLN), with a 14-W 1.06- μ m Nd:YAG laser to generate a signal at 1.7 μ m and an idler at 2.8 μ m. Mixing of the two waves at the same crystal temperature and grating spacing yielded emission in the mid IR. This technique avoids the mid-IR absorption-high-threshold problem, which has limited the cw performance of PPLN OPOs at wavelengths beyond 4 μ m. Provided that tunability is not required, this method is a simple alternative to multiple-crystal configurations.				
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Coherent sources in the 4–5- μm region are needed for a variety of applications, including chemical monitoring, biomedical applications, spectroscopy, and atmospheric and environmental sensing. Although pulsed emission is readily obtained at these wavelengths, high-power cw sources for solid-state laser devices are essentially nonexistent. Quantum-cascade lasers have yielded powers of up to 150 mW in this wavelength range.^{1,2} These lasers, however, require liquid-nitrogen temperatures for achievement of this level of performance. Recent improvements in the fabrication of periodically poled LiNbO_3 (PPLN; Ref. 3) have made possible the development of high-power cw optical parametric oscillators (OPO's) for the conversion of 1- μm laser emission to wavelengths of up to 4 μm .^{4–7} Output at wavelengths further into the IR, however, is difficult to obtain because of optical absorption by the LiNbO_3 , which results in a high threshold.^{8,9} The cw PPLN OPO threshold and related thermal issues are discussed in Ref. 10. To date, only very low power has been achieved at wavelengths just slightly longer than 4 μm for cw operation in a PPLN OPO.⁶ To avoid the high-threshold problem, we have used a two-step nonlinear conversion process within the same PPLN crystal to obtain mid-IR output. In the first step a 1- μm Nd:YAG laser pumps a singly resonant OPO ring cavity to generate signal and idler wavelengths at 1.7 μm (resonant) and 2.8 μm , respectively. In the second step the resonant 1.7- μm and nonresonant 2.8- μm waves mix to generate light at 4.3 μm . Since this mixing, or difference frequency generation (DFG), is distinct from the optical parametric oscillation process, the strong optical absorption beyond 4 μm does not affect the threshold of the overall device. Furthermore, since both processes occur in the same crystal, there are no additional alignment issues beyond those of a standard OPO resonator.

A schematic of our setup is shown in Fig. 1. The four-mirror ring cavity was similar to that used in previously reported OPO work at 2.9 μm .⁷ The mirrors in this effort were coated for high transmission at 1.06, 2.8, and 4.5 μm and high reflection at 1.7 μm . The two flat mirrors were separated by 6.5 cm, and the two concave mirrors (10-cm radius of curvature) were separated by 14.5 cm. The total cavity length was ~ 45 cm and formed a mode-waist diameter of ~ 70 μm within the crystal. The 5-cm-long PPLN crystal, fabricated by Crystal Technology, had three different grating periods, 30.34, 30.5, and 30.66 μm for testing. The crystal was temperature tuned in an oven that could reach a maximum of 230 $^\circ\text{C}$. The PPLN was pumped by a commercial cw Nd:YAG laser from Lightwave Electronics, which lased on ~ 10 longitudinal modes at 1.06 μm . The signal and idler wavelengths were measured with a Burleigh WA-1000-IR wavemeter. The DFG output was measured with a pyroelectric power meter.

In general, for a single temperature, two different consecutive PPLN gratings would be required for phase matching of the optical parametric oscillation and DFG processes. However, our calculations predicted that there are conditions under which a single grating can be used to perform both nonlinear processes at a specific temperature. Using the often-cited LiNbO_3 Sellmeier equation from Edwards and Lawrence¹¹ and a more recent equation from Jundt,¹² we calculated the PPLN DFG grating period that was required for phase matching of the signal and the idler generated from a specific PPLN OPO grating period as a function of temperature. As shown in

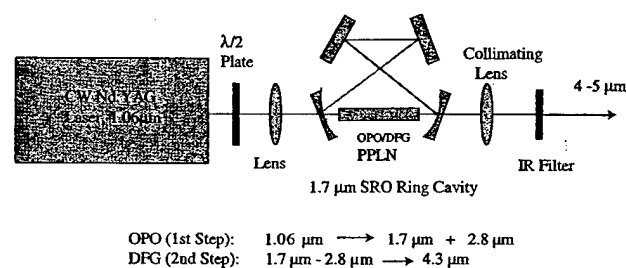


Fig. 1. Optical layout for the PPLN OPO-DFG experiment. SRO, singly resonant optical. See text for other definitions.

Fig. 2, which was calculated for signal and idler wavelengths derived from a 30.34- μm OPO grating period, the DFG and optical parametric oscillation grating periods are equal at one specific temperature, which is dependent on the Sellmeier expression used. For the Sellmeier expression of Ref. 11, simultaneous phase matching by use of a grating period of 30.34 μm occurs at 212°C. This phase matching yields a DFG output at 4.578 μm , an OPO signal at 1.727 μm , and an idler at 2.773 μm . For the Sellmeier expression of Ref. 12, the analysis yields 4.331- μm DFG output at 202°C, with OPO wavelengths at 1.709 and 2.823 μm . The results for similar calculations with the other two PPLN grating periods, 30.5 and 30.66 μm , are listed in Table 1.

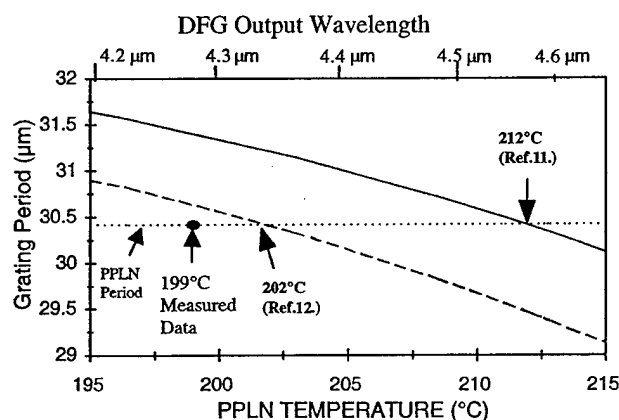


Fig. 2. Required DFG grating period for phase matching of the signal and the idler from a 30.34- μm PPLN OPO as a function of crystal temperature. The solid curve was calculated from the Sellmeier equation in Ref. 11, and the dashed curve was derived with the Eq. from Ref. 12. The dotted line denotes the actual grating period of the crystal. The solid oval shows the temperature at which simultaneous optical parametric oscillation and DFG phase matching was achieved.

Tests were carried out with all three PPLN gratings. The DFG signal was monitored as the crystal temperature was varied around the predicted temperatures. Measurable DFG output power is very sensitive to temperature variation because of the stringent phase-matching condition. The experimental results, listed in Table 1 for comparison with the theoretical predictions, are in closer agreement with the calculations derived from the Sellmeier equation of Ref. 12. Our data thus indicate that the Sellmeier equation from Ref. 12 is more accurate for calculating the refractive index of LiNbO_3 in the 4–5- μm wavelength region.

The performance of the optical parametric oscillator–difference frequency generator (OPO–DFG) resonator (Fig. 1) with the PPLN crystal with the 30.5 μm grating is shown in Fig. 3. At the maximum 1.06- μm pump power of 14.2 W (measured at the input mirror), we obtained 150 mW of cw output at 4.3 μm (measured through a 90%-transmissive long-pass IR filter). To our knowledge, this is the highest cw output power in the 4–5- μm region ever reported for a solid-state laser device.

Because the 1- μm Nd:YAG laser has a spectral bandwidth of 0.02 nm (5 GHz) and the resonant signal at 1.7 μm in the OPO ring cavity is a single frequency, the spectral bandwidth at 2.8 μm should be ~ 0.13 nm, and the bandwidth at 4.3 μm should be ~ 0.31 nm. Using the Sellmeier expression of Ref. 12, we calculated the OPO spectral and temperature acceptance bandwidths near 1.7 μm to be 4.2 nm and 3.1°C, respectively. Similar calculations for the DFG process yielded spectral and temperature acceptance bandwidths near 1.7 μm of 0.36 nm and 5.5°C, respectively. This 0.36-nm bandwidth leads to a tunable bandwidth of 4.6 nm near 4.3 μm for our OPO–DFG device.

Since the optical parametric oscillation and DFG processes occur in the same PPLN crystal and are not independent, the resulting tunability of the OPO–DFG

Table 1. Comparison of the Experimental Data and Predictions (Temperatures and Wavelengths) for Simultaneous Phase-Matched Optical Parametric Oscillation and DFG at Three Different PPLN Grating Periods

Grating Period (μm)	T ($^{\circ}\text{C}$)	Wavelength (μm)		
		OPO Signal	OPO Idler	DFG
30.34				
Ref. 11 (Calc.)	212	1.727	2.773	4.578
Ref. 12 (Calc.)	202	1.709	2.823	4.331
Measured	199 ^a	1.707 ^a	2.829 ^a	4.304 ^b
30.5				
Ref. 11 (Calc.)	182	1.725	2.778	4.551
Ref. 12 (Calc.)	171	1.707	2.827	4.309
Measured	169 ^a	1.705 ^a	2.833 ^a	4.282 ^b
30.66				
Ref. 11 (Calc.)	148	1.720	2.791	4.482
Ref. 12 (Calc.)	138	1.706	2.831	4.293
Measured	137 ^a	1.703 ^a	2.837 ^a	4.261 ^b

^aDirectly measured data.

^bCalculated from measured OPO signal and idler wavelengths.

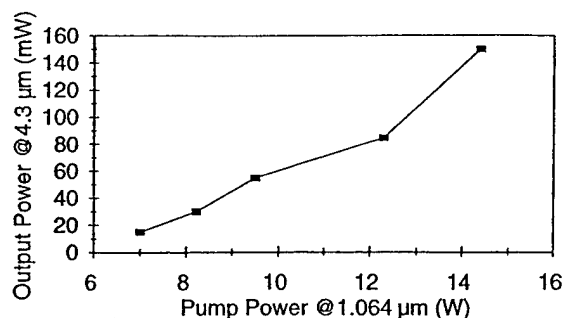


Fig. 3. DFG output power versus Nd:YAG pump power for a single-period (30.5- μm) PPLN crystal.

device is significantly less than the independent bandwidth parameters would suggest. We observed the temperature bandwidth of our device to be less than 1°C. The wavelength tunability of our device by temperature is less than 2 nm, which is beyond the resolution of our current diagnostics.

We have demonstrated 150 mW of cw 4.3- μm output, using DFG in a singly resonant PPLN OPO. Our two-step wavelength-conversion approach provides a simple way to extend the useful wavelength range of PPLN into the region in which optical absorption becomes problematic. A low threshold and simple design are key features of this approach. Clearly our device does not provide significant wavelength tunability, owing to the unique phase-matching conditions. Wider tunability, however, can be achieved by use of two separate temperature-controlled PPLN crystals for the optical parametric oscillation and DFG processes. However, the alignment of such a device is more difficult than for the single PPLN device described above. We are currently pursuing the two-crystal approach and will discuss our results at a later date. Additionally, our data identify the most accurate LiNbO₃ Sell-

meier equation in the 4.3–4.5- μm region, which will enable us to design new PPLN crystals for other IR wavelengths and tunable operation.

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